Investigation of Power Quality Enhancement in Grid-Connected Solar System

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Abstract. Grid connected solar PV systems mostly face problems related to power quality like harmonic distortion, voltage fluctuation and slow response under varying sunlight. To overcome this issue the paper introduces a system which provides optimal solution to the problems by using combination of advanced Power electron components and smart control technique to improve overall efficiency and stability. In the proposed system, the PV array is connected through an interleaved high gain coupled inductor DC-DC boost converter. This converter helps to reduce ripple in input current and maintain a steady DC-link voltage. To extract maximum power from the PV panel a hybrid IPSO-NN MPPT method is used, which contains Particle Swarm optimization with Neural Network. This approach ensures that the system is quicker and more accurate in tracking maximum power point even under varying weather conditions or partial shading. The regulated DC power is then supplied to a silicon carbide (Sic) based three level Neutral point clamped (NPC) inverter. This inverter works based on Finite Control Set Model Predictive Control (FCS-MPC) which make the system fast response to changes and improved quality of the output grid current. This helps in reducing switching losses, improving harmonic performance, and fast transient response. The LCL filter with active damping helps to reduce the switching harmonics and ensures the system sends clean, required current into the network. To improve grid support Virtual Synchronous Machine (VSM) based grid-farming is used, which provides virtual inertia, improved voltage stability, and adaptive droop-based power sharing. Experimental and simulation results show the significant improvement in total harmonic distortion (THD) below 3%, faster MPPT tracking, better dynamic stability, and overall high-power quality at PCC.

Keywords: grid-connected solar systems, Total harmonic distortion, hybrid IPSO-NN MPPT technique, virtual Synchronous Machine, Finite Control Set Model Predictive Control (FCS-MPC).

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1 Introduction

Solar photovoltaic (PV) technology has become one of the most rapidly growing renewable energy sources because it is eco-friendly, easy to expand and cheaper to install. However, as the solar PV systems become one of the most commonly used one in distribution networks, problems like poor power quality, unstable grids, and low reliability are increased. Modern grid-connected PV systems not only provide clean power but also meet strict power quality standards, react quickly to changes in sunlight, support the grid during disturbances, and work smoothly with the existing electrical system [8]. To reach this, the system needs more advanced converters, intelligent control algorithms, and efficient grid integration techniques.

One of the main challenges in grid connected PV system is that sunlight is never stable. It constantly changes because of cloud, shading, and weather. These changes can directly affect the voltage and current of the photovoltaic, which makes the system act unstable. In traditional MPPT method like perturb & observe work well under stable sunlight but their performance is very low under varying sunlight because sometimes they get confused, they take too much time to settle and sometimes even track wrong power point [5]. To overcome these drawbacks, the proposed method uses hybrid and optimization-based algorithms. These advanced methods react fast to the changes and help the PV to gain more power efficiently and smoothly.

In this case, metaheuristic algorithms are used because they are flexibility and it can easily adapt to changing operating conditions. Among these, Particle Swarm Optimization is commonly used in MPPT because they effectively search for the best operating point. But normal PSO may be slow and sometimes fails under complex shading [1]. To address these issues, advanced versions like Improved PSO, hybrid PSO, and neural network assisted optimization have been developed. In this paper, we implement a hybrid improved PSO with Neural Network MPPT method to improve both speed and accuracy. The neural network first predicts a approximate Maximum Power Point based on past irradiation and voltage data, and then the IPSO algorithm adjusts the operating point. This combined approach results in a highly efficient, stable, and intelligent MPPT strategy, ideal for real time PV applications [3].

Another major challenge in using solar PV system to grid is designing and providing efficient conditioning unit. In this system DC -DC converter plays a major role because it helps to regulate varying PV panel voltage and maintain a stable DC link voltage for the inverter. Most of the traditional systems use boot converters but they have some drawbacks like they create high stress on switching device, limited voltage gain and produce more ripple at high power levels. To overcome this problem, the system uses an advanced interleaved high-gain boost converter which helps to reduce input current ripple, provides high voltage gain, and improves overall efficiency. The use of coupled inductors is to improve the further voltage gain without pushing the duty cycle to extreme values. Overall this makes the converter more suitable for the grid connected solar PV systems [4].

Along with converter, the inverter of the system also plays a major role in making the system more efficient and maintaining good power quality. Most commonly used traditional inverter is two level voltage source inverters (VSIs)but they produce lot of switching harmonics. Because of this, it required large filters to meet the grid standards which leads to bulky system and low efficiency of the system. To overcome this problem, modern power electronic design now includes multilevel inverters mainly Neutral Point Clamped (NPC). These inverters help to reduce total harmonic distortion (THD), switching losses and electromagnetic interference. To achieve higher switching frequencies and better efficiency than conventional devices, the system uses advanced semiconductor devices called silicon carbide (SiC) based three level NPC inverter. This makes the entire conversation process more reliable and more suitable for renewable energy applications

To get the best performance of the inverter, the system needs a smart and fast control method. One of the most advanced techniques used in recent years is Model predictive control (MPC). When compared to traditional PI controller MPC not only react to the errors but also predict the behavior of the voltage and current in next instant using mathematical model system. Based on this it chooses the best switching state in real time which makes the system faster, more stable, and more accurate. It also helps to reduce distortions and handle limitations like voltage drop or raise. In this system a special type of control called Finite Control Set MPC (FCS-MPC) is used especially for power electronic systems because it directly works with the limited number of switching states available in an inverter. By combining MPC with a multilevel SiC inverter, the system achieves can achieve maximum voltage tracking and fast response to grid disturbances [7].

Even after using advanced inverter control, the system still needs a proper grid filter to minimize the high-frequency harmonics before sending power into the grid. Among the different types of filters, the LCL filter is one of the best one as it removes harmonics more effectively and uses smaller components compared to basic L or LC filters. But LCL filters also have face some challenges like they create a resonance effect, which may make because instability of the system if it was not controlled properly [9]. To avoid this, we use active damping methods like capacitor-current feedback or virtual resistance. These techniques help to control the resonance without adding big resistors, which would otherwise reduce efficiency. In this work, we used an LCL filter with active damping to keep the system more stable, to reduce THD and to meet power quality standards. This makes that the power delivered to the grid is without disturbance, secure and reliable.

As we add more renewable energy to the grid, PV inverters are required to support the grid more effectively. Now a day the grid expects inverters to do much more than just supply clean power. They also need to support the grid by keeping the stable voltage, balancing the frequency, providing needed reactive power, and staying connected during grid faults. The inverters which are followed by the traditional grid mainly depend on Phase Locked Loops. They can only follow the grid but they cannot help to make the stable system during disturbances. Because of this limitation, recent inverter control strategies are using grid forming approaches. In these methods, the inverter acts like a Virtual Synchronous Machine, this shows the behaviour of traditional synchronous generators. A virtual synchronous machine-based inverter can provide virtual inertia and damping, helping the grid remain stable, mainly in weak grids, where stability problems are more common [3]. In this project, a VSM based grid interface is used to improve dynamic stability, make better power sharing, and support the grid during sudden changes. This makes the overall system stronger and more stable.

Overall, the system well designed to improve the power quality and stability of grid-connected solar PV devices. The system uses high-efficiency interleaved DC–DC converter, an intelligent IPSO-NN based MPPT algorithm, SiC-based multilevel inverter, MPC-based control, an LCL filter with active damping, and a VSM-based grid interface. By combining all these modern technologies, the system achieves better harmonic performance, more accurate MPPT tracking, faster dynamic response, and stronger grid support. These improvements make the entire system more efficient, more stable, and well prepared for future large-scale renewable energy integration [10].

2 Literature survey

Kumar et al. (2023) introduced a hybrid MPPT method, which integrates a PSO trained machine learning model with the Flying Squirrel Search algorithm. The combination is designed to improve the speed of reaching solution of the system and improve the stability of the system during partial shading and fast changing irradiance conditions. The results show that the combining predictions based on the data with a global metaheuristic approach increases the accuracy of tracking and reduces the fluctuations at steady state compared to conventional MPPT methods. This study shows the ability of hybrid machine learning based metaheuristic approaches to get high energy efficiency in real world PV environments. However, the study focuses on simulation results and may face some practical implementation challenges under high dynamic real-world conditions [1].

Al-Majidi et al. (2020) investigated the problem of slow MPPT response and high oscillations in conventional tracking techniques during rapid change in sunlight. To address this, the system uses PSO-trained feedforward neural-network -based MPPT method, where the neural network predicts the maximum power point using the collected PV data during the experiment. The usage of Particle Swarm Optimization in the system helps in optimizing the NN parameters and improving prediction accuracy. Their approach reduced settling time and minimized oscillations around the MPP, which shows that the system provides faster dynamic performance compared to classical MPPT algorithms. The paper highlights the benefit of combining soft-computing techniques with optimization for improved power extraction. However, the method still relies on high-quality training data, making it less effective when operating outside trained environmental conditions [2].

Valarmathy et al. (2024) proposed a high gain interleaved boost derived converters and various gain an extension technique, which includes coupled inductors, switched capacitors, and active clamps, for PV applications. In this paper the study shows the trade-offs between voltage gain, efficiency, component stress, and circuit complexity. Earlier works presented coupled inductor high gain designs for PV systems where the panel voltage is below the required DC-link voltage. The interleaved coupled-inductor approach helps to reduce the input current variations and allows each phase to operate at a high switching frequency, which is then reduces the downstream filter requirements and improves the overall power quality. But the higher circuit complexity and more parts could limit its use in compact or budget-friendly PV setups [3].

Zhang et al. (2023) investigated Model Predictive Control Strategies for Multilevel Inverters where they discussed the drawbacks of traditional PI-based control in handling fast dynamic changes and nonlinear switching behaviors. The issues like limited constraint handling, slower response time, and higher harmonic distortion are one of the major reasons in conventional controllers that affect the overall efficiency. To overcome these challenges, they proposed a Finite Control Set Model Predictive Control approach that predicts future inverter behavior and selects the optimal switching state in real time. Their method showed significant improvements in dynamic response, THD reduction, and switching efficiency, especially when combined with SiC-based multilevel inverter hardware. However, the paper has some limitations such as high computational demand, strong dependency on accurate system modeling, and the complexity of tuning the cost function for stable real-time performance [4].

Martinez et al. (2023) investigated Grid-Forming Control and Virtual Synchronous Machine Strategies for high level PV Systems where they discussed the limitations of traditional grid-based inverters, especially their weak support during disturbances and poor behavior in low-inertia grids. The authors explained how Virtual Synchronous

Machines (VSM) and synchronverters replicate the dynamics of real synchronous generators to provide virtual inertia, droop response, and improved stability. Their work highlighted that VSM-based grid-forming control offers better frequency regulation, smoother synchronization, and enhanced transient performance compared to conventional PLL-based methods [6]. To provide more control, the system uses VSM with fast inner-loop Model Predictive Control (MPC). This helps to achieve precise current regulation and to provide strong grid-support during faults and fluctuations. However, the paper has some limitations such as increased control complexity, higher computational requirements, and the need for accurate tuning of inertia and damping parameters for stable operation under varying grid conditions.

Khan et al. (2023) investigated System level power quality enhancement in grid connected PV systems where they discussed the challenges of maintaining low THD, stable voltage, and proper harmonic suppression in double-stage PV architectures. Their system consists of a DC–DC converter, inverter stage, `and LCL grid filter. They highlighted issues like switching harmonics, weak-grid instability, and poor dynamic response. To solve these problems, they combined advanced converter topologies, intelligent MPPT algorithms, and active damping techniques to enhance power quality at the PCC. It shows the improvements in THD reduction, better voltage regulation across various grid conditions. However, the paper also has some limitations like lack of integrated testing with SiC-based multilevel inverters and the absence of hybrid MPPT techniques like IPSO-NN combined with VSM-based grid-forming control within a single unified platform [5].

3 Methodology

As the solar PV system is used widely, modern power networks expect not only efficient energy extraction but also to deliver clean, stable power to the grid. Most of the conventional PV systems still depends on basic boot converters based MPPT, two-level inverters and inverse LCL filters which have many drawbacks. Traditional MPPT methods response slowly under varying sunlight and oscillate under partial shading. Simple boost converters also provide high voltage gain without using very large duty cycles which increase losses and increase the stress on the switching devices. This leads to difficult in maintaining a stable DC-link. Two-level inverters produce more switching harmonics and therefore there is a need if using large filters because PI based control often reacts slowly and performs poorly under weak grid conditions. Most of the system uses LCL filters but their passive design create resonance problem and they cannot adapt the changes that occur during grid impedance. Hence, all these limitations make the conventional system less efficient and reliable

The proposed system addresses the limitations of traditional PV system by introducing the improvements at each stage of the power conversion process. An interleaved coupled-inductor high-gain converter replaces the traditional boost converter, which delivers the high voltage gain with low ripple and less stress on the devices. The IPSO-NN MPPT algorithm makes fast and accurate tracking of the maximum power point, under partial shading, doing better than classical P&O and standard PSO methods. On the AC side, silicon based three levels NPC inverter allows higher switching frequency, less losses, reduced electromagnetic noise, and better harmonic performance. This inverter is controlled using FCS-MPC, which predicts system behaviour and selects the best switching state in real time, clearly improving the performance of the system to sudden changes. An actively controlled LCL filter to reduce resonance and keeps low total harmonic distortion across a wide range of grid conditions. In addition, a VSM based grid forming layer provides virtual inertia, adaptive droop control, and enhanced fault ride through capability, allowing the PV system to actively support grid stability. These improvements create a complete, future ready solar PV solution that offers high efficiency, strong dynamic performance, and reliable, high quality power injection into the grid.

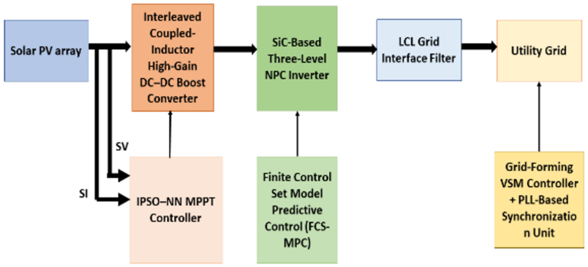


Fig.1. Block Diagram of the Proposed Solar PV Power Conversion System

The Fig.1 shows the working block diagram of the proposed system. At first the solar PV array generates a changing DC voltage depending on the variation in sunlight which is then fed up into the interleaved coupled -inductor boost converter. The IPSO based neural network MPPT continuously monitor the PV voltage and current and quickly adjust the duty cycle to provide maximum power extraction. The boosted and stabilized DC link voltage is then given to the SiC based three level inverters where model predictive control chooses the best switching state in real time and help the inverter to respond quickly and produce output with very low harmonic distortion. The inverter output is then given to LCL filter where the resonance is removed by active damping to provide clean and smooth sinusoidal current to the grid. At the grid side, the Virtual Synchronous Machine (VSM) combined with PLL make sure that the inverter is properly synchronized with the grid. It also provides virtual inertia and improve stability during any disturbances. By this the system maintains high efficiency stable power flow and improved power quality.

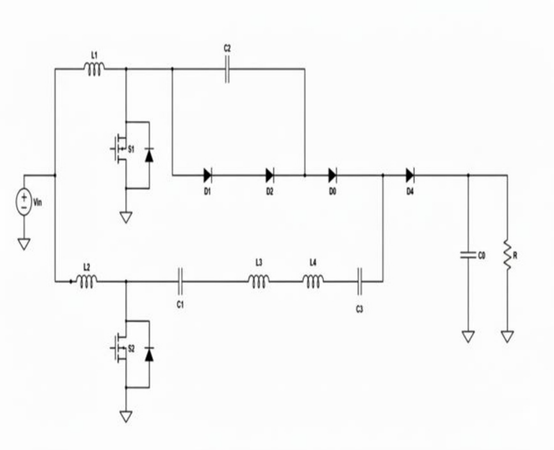


Fig.2. Interleaved coupled inductor boost converter

Fig.2 shows the interleaved coupled-inductor boost converter, which operates has two switching paths, where each path contains a MOSFET switch (S1 and S2), pair of coupled inductor pair and diode (D1 and D2). The two switches work in opposite timing so when one switch is ON the other switch is OFF. When switch S1 and S2 is turned ON, the corresponding primary inductor stores energy. When the switch turns OFF, this stored energy is transferred through the secondary winding and the diode (D_1 or D_2) to the output. As the two windings are magnetically coupled, the converter boosts the output voltage more effectively without using very high duty cycle. The interleaving action reduces the input current ripple because the currents from both phases flow in opposite timing and their waveforms overlap in way that it cancels out the high-frequency changes. This also reduce the conduction loss, Electromagnetic interference, and stress on the MOSFETs and inductors. The output capacitor C0 stabilizes the boosted DC voltage before it is given to the next stage. By combining phase-shifted interleaving and coupled-inductor voltage enhancement, this topology achieves high voltage gain, improved efficiency, reduced ripple, and better dynamic performance.

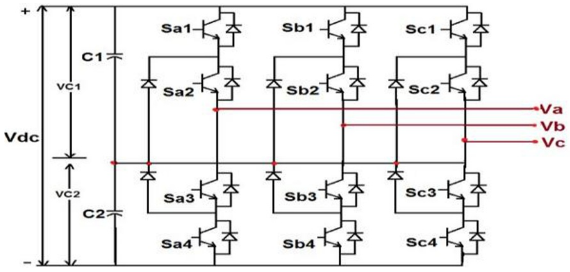


Fig.3. SiC based three-level inverter

Fig.3 shows the three-phase, three-level Neutral Point Clamped (NPC) inverter is commonly used in high-power applications because it can produce multilevel output voltages with lower harmonic distortion and low switching stress. In this topology, the DC-link voltage V_{dc} is divided into two equal parts using capacitors $C_1$and C_1 and it is given by,

$$V_{dc} = V_{c1} + V_{c2} \tag{1}$$

Where, $V_{c1} = V_{c2} = \frac{V_{dc}}{2}$

This configuration creates a neutral point between the capacitors and allows it to generate three different voltage levels for each phase. In each phase four IGBTs and two clamping diodes and combination of their switching states defines the phase output voltage V_{aN} . When the upper switches $S_{a1} and\ S_{a2}$are ON, the output is connected to the positive DC bus. It is written as,

$$V_{aN} = +\frac{V_{dc}}{2} \tag{2}$$

When the middle switches $S_{a3}\ and\ \ S_{a4}$ are ON, the output is connected to the negative DC bus and it is written as,

$$V_{aN} = -\frac{V_{dc}}{2} \tag{3}$$

The same switching logic applies to phase B and phase C. The line voltages are derived from the difference between phase voltage, such as,

$$V_{ab} = V_{aN} - V_{bN},\ V_{bc} = V_{bN} - V_{cN},\ V_{ca} = V_{cN} - V_{aN} \tag{4}$$

As each phase can produce three voltage levels, the line-to-line voltages combine to form five distinct levels,

$$V_{line} \in \left\{V_{dc} - \frac{V_{dc}}{2}, 0, \frac{V_{dc}}{2}, V_{dc}\right\} \tag{5}$$

This multilevel output enhances power quality by minimizing total harmonic distortion (THD) and electromagnetic interference (EMI) and also improving efficiency. The NPC inverter is highly suitable for grid-connected renewable energy systems and indw5ustrial motor drives that require efficient voltage control.

For LCL filter, the resonant frequency is one of the most important values because it shows the point where the filter naturally tends to oscillate. If this resonance drops inside the controller's working range, the system may become unstable or start vibrating. The resonant frequency can be calculated as,

$$f_{res} = \frac{1}{2\pi}\sqrt{\frac{L_1+L_2}{L_1L_2C}} \tag{6}$$

The current ripple in the inverter mostly depends on the factors like DC-link voltage, duty cycle, switching frequency and size of the inductor. If the inductor value or the switching frequency is increased, the ripple reduced, which helps in producing a clean and more stable output. The ripple current can be calculated as,

$$\Delta I = \frac{V_{dc} \cdot D(1-D)}{L \cdot f_s} \tag{7}$$

The grid current is depends on the inverter output voltage that flows through the two inductors and the capacitor in the LCL filter. These components work together to provide a smooth current without unwanted high-frequency harmonics before the power is give into the grid. The grid current is given by:

$$I_{grid}(s) = \frac{V_{inv}(s)}{L_1 s + \frac{1}{C_s} + L_2 s} \tag{8}$$

The voltage across the filter capacitor plays an important role in the overall behavior of the LCL filter. It is directly depending on the current that comes from the inverter and this voltage acts as a buffer that helps the system to control high-frequency components. By monitoring and controlling the capacitor voltage, the system can apply active damping, which prevents oscillations and keeps the inverter stable. It also helps in reducing high-frequency harmonics, ensuring that the power delivered to the grid remains smooth and clean. The capacitor voltage is given by,

$$V_C(s) = I_{inv}(s) \cdot \frac{1}{C_s} \tag{9}$$

To prevent unwanted resonance in LCL filter, a damping resistor is added so the system. This resistor can be a passive damping or it can be added virtually through the control algorithm which is active damping. Choosing the right value of this damping resistance is important because it helps the filter to stay stable without affecting the efficiency. The optimal damping value is given by,

$$R_d = \frac{1}{3\omega C} \tag{10}$$

Total Harmonic Distortion (THD) shows the stability and reliability of the system. In an ideal system, the inverter should produce a perfect sinusoidal waveform, but in reality, switching devices and nonlinear loads create harmonic components at different frequencies. THD helps to validate the unwanted harmonics that affect the original signal. The low THD value shows the inverter is producing smooth power, improve efficiency, and ensure smoother grid interaction. The THD is calculated using,

$$THD = \sqrt{\sum_{n=2}^{\infty}(\frac{V_n}{V_1})^2 * 100\%} \tag{11}$$

4 Result and discussion

The hardware MPPT result clearly shows a ‘two-stage pattern, which is shown in Fig.4. In the beginning, the solar voltage, current, and power waveforms shows clear spikes and oscillations. These early fluctuations occur because the MPPT controller is still trying to find the maximum power point. It works by quickly varying the duty cycle, which creates short, temporary changes in the signal due to the converter’s switching action and minor measurement of noise. After this initial search period, the controller identifies the best operating point, and all three waveforms are move into a stable region where the voltage and current stay constant, and the power output settles into a smooth curve with very little ripple. This stable part of the graph shows that the IPSO based neural network MPPT has successfully reached steady state and is exactly keeping the system at the maximum power point. The small and stable ripple seen after settling is expected and represents the small adjustments the algorithm continually makes to keep the PV panel at its ideal operating condition. Overall, the waveform clearly reflects fast MPPT convergence followed by stable and efficient power tracking.

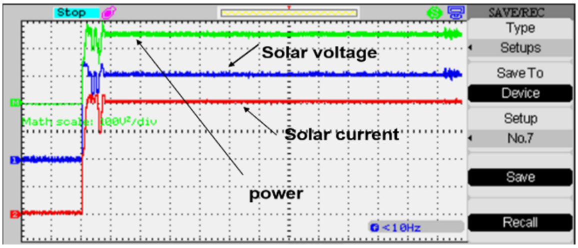
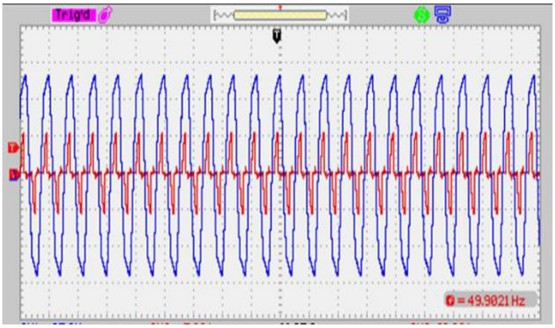
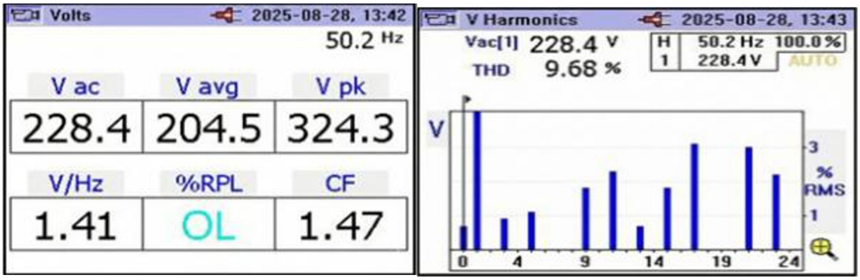


Fig.4 MPPT tracking hardware result

The hardware output of the proposed system showing highly stable and clean sinusoidal waveform at the inverter stage indicates the performance of the system. As shown in the Fig.6, both the voltage and current waveforms are clean and smoothly sinusoidal with low visible distortion. This ensures that the LCL filter and the control strategy used in the proposed system are working well. The filter used in the system effectively removes the high-frequency harmonics and controller maintain the system stable which result in a neat and smooth resulting high-quality waveform output. The measured RMS voltage is approximately 228.4 V with a peak value of 324.3 V which matches expected grid specifications. The low THD value of the proposed system which is around 2.8% shows that the system is more efficient and enhance power quality with good reliability in inverter operation. Whereas, as shown in the Fig.5 shows, the distorted waveform of the existing system and TDH value of 9.86 % shows its inability to maintain proper voltage quality and harmonic suppression. This comparison highlights the efficiency, stability, reliability of the proposed system when compared to the existing system.




Volts 2025-08-28, 13:42
50.2 Hz

V ac	V avg	V pk
228.4	204.5	324.3
V/Hz	%RPL	CF
1.41	OL	1.47

V Harmonics 2025-08-28, 13:43
Vac[1] 228.4 V
THD 9.68 %
H 1 50.2 Hz 100.0 % 228.4 V AUTO

Fig.5.THD in the Proposed System

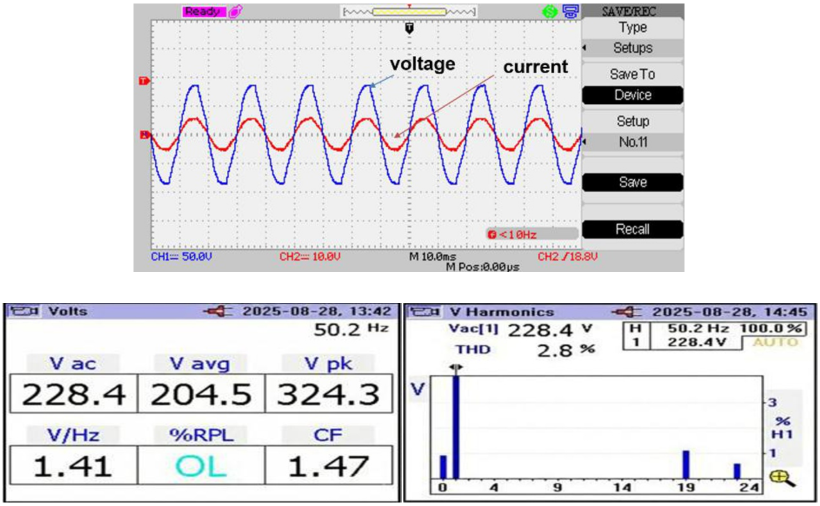


Fig.6. THD Reduction in the Proposed System

The Fig.7 shows that the inverter voltage perfectly matches the grid voltage both in amplitude and phase. The two waveforms align smoothly, which shows that the proposed system is able to synchronize with the grid correctly. This means the Phase Locked Loop and the control methods for inverters are working properly, which allows the inverter to deliver power to the grid without creating any problem. The clean, sinusoidal shape of both signals confirms that the system stays stable and keeps low phase errors during synchronization.

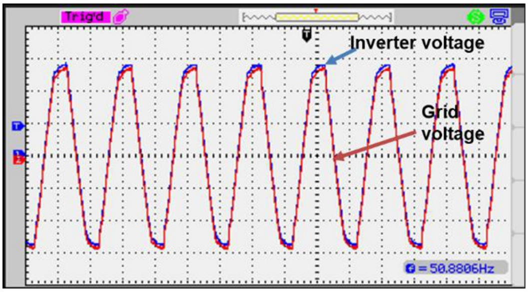


Fig.7. In-Phase Synchronization of Inverter Voltage and Grid Voltage

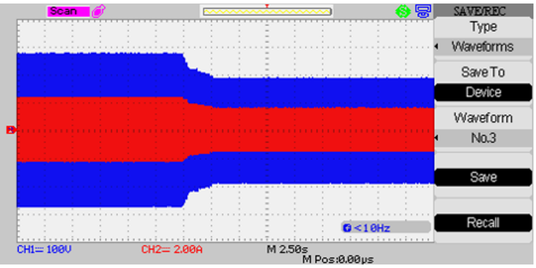


Fig.8. Close-Up View Showing Precise Overlap of Inverter and Grid Voltages

Fig.8 shows close-up view of the waveform further confirms the performance, as the inverter and grid voltages overlap almost exactly on top of each other with only minimal difference. This overlap shows the precision of the synchronization mechanism and proves that the system operates with very low phase error. The clean sinusoidal patterns in both display windows also show that the inverter maintains stable, high-quality output even during grid coupling. Overall, this result highlights the effectiveness, reliability, and accuracy of the proposed inverter system in achieving seamless grid integration.

5 Conclusion

In conclusion, the proposed system addresses the limitations of the conventional designs by offering fast MPPT response, high voltage gain, low harmonic distortion and strong grid support. These are achieved due to the usage of components like an interleaved coupled inductor boost converter which is used to achieve higher and more stable DC link voltage with low losses , IPSO-NN MPPT method to improve tracking, low oscillation and better performance under varying sunlight, Sic based multilevel inverter combined with model predictive control which improves switching efficiency, reduce THD and enhance dynamic response and LCL filter with active damping reduces high frequency harmonics and maintain stability across different grid conditions. Along with that to strengthen the grid interaction VSM control strategy was included which provides better inertia support, smooth synchronisation and improves the capability of the system. Overall, the proposed system provides higher than efficiency, better power quality and stronger grid comparability which makes it more suitable solution for the future renewable energy applications with high PV penetration.

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